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THE EFFECT OF RUBBER HANDNESS ON THE COEFFICIENT OF STATIC FRICTION WITHOUT LUBRICATION

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- USSR -

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THE EFFECT OF RUBBER HARDNESS ON THE COEFFICIENT OF STATIC FRICTION WITHOUT LUBRICATION

- U S S R -

[Following is a translation of the article "Vliyaniye tverdosti reziny na koeffitsient Staticheskogo treniya bez smuzki" (English version above) by S. B. Ratner and V. D. Sokol'skaya in Doklady Akademii Nauk SSSR (Reports of the Academy of Sciences USSR), Vol XCIX, No 3, Moscow, 1954, pages 431-434.]

In instances of friction of rubber against hard materials the friction coefficient μ depends (1-3) on load N as per formula

$$\mu = \mu_{\infty} + \frac{F_0}{N}, \qquad (1)$$

where μ_{∞} - minimal value, which determines its magnitude at great loads (when $F_0 \ll N$); F_0 is the tangential component of the force of molecular attraction between bodies and determines the value of μ at small loads when item μ_{∞} is relatively small.*

* When the article was in print, there appeared a work (9) on the connection between the force of friction of rest and "elementary forces". In that work it is shown that the smoother the surface the greater the role of elementary forces which come into being between bodies in contact. These findings reinforce the concepts on the basis of which we proceed. There remains only a divergence in terminology. Namely,

This formula is based on the Deryagin theory of the binominal law of friction for solid bodies. At the same time, a fully identical character of effect of load on friction of solid bodies and highly polymeric substances has been experimentally demonstrated by means of friction of crisscrossing threads.

Therefore, with regard to the effect of load, an identical character of phenomenon for hard (solid) bodies and rubber takes place (1-3) in friction of common samples as well. As far as the detailed appearance of the formula is concerned, it should not be identical for hard bodies and rubber, since the latter becomes much more deformed under the influence of load, and furthermore, the difference in the hardness of rubber itself cannot fail to have its effect, too. Indeed, according to this formula, F_0 is a tangent of the angle of inclination of the straight line in coordinates $\mu - 1/N$, if $F_0 = \text{const}$. However, a substantial deviation from the rectilinear is observable (2) in Fig. 1a for soft rubbers.

In this book we have attempted to introduce into the formula (1) more precise definitions, which take into consideration two experimental facts observable in this illustration (Fig. 1): the angle of inclination (i.e. F_0) decreases with the increase of $1/N$ (i.e. with decrease of load); this effect is the greater the softer the rubber.

Both phenomena may be comprehended in the light of B.V. Deryagin's theory (4), according to which F_0 is

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"elementary forces" of friction are connected with molecular coarseness (μ_1) which we had called (3) micro-coarseness, but it should be called ultra-micro-coarseness (4) because the term micro-coarseness is usually applied to surfaces "for which the friction of rest can be explained with the aid of the known model of two files" (9); this latter (μ_2) we have called (3) macro-coarseness, which is not accepted, because this term is employed for unevenness discernable with the naked eye.
Let us also correct several typographic errors in the article (3): On page 47 the third line from the bottom reads $\mu_\infty = \mu_2(1-\mu_2)$, while it should read $\mu_\infty = \mu_1(1+\mu_2)$; on page 49 the 14th line from the bottom should read μ_2 instead of μ_∞; in Table 2 quantity F_0 is given in grams/cm2 and not in kilograms/cm2.

proportional to the area of true contact, which had received experimental confirmation in the research into friction of diverse bodies (1-5).

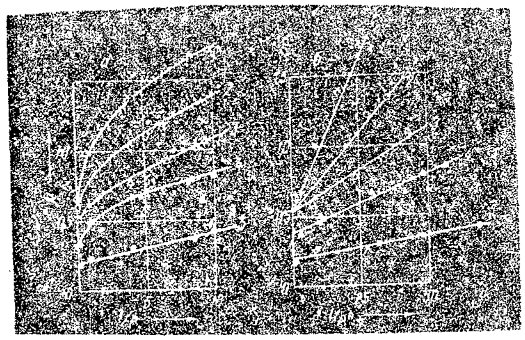

Figure 1. Connection between the coefficient of friction μ and specific unit load P (in kilograms/cm2) in the friction of base SKN-26 rubber against steel, the rubber being filled by various amounts of graphite S (in parts by weight) and having a hardness h: 1 - C = 10, h = 0.45, 2 - C = 45, h = 0.65; 3 - C = 60, h = 0.68; 4 - C = 80, h = 0.73; 5 - C = 120, h = 0.83,
a - system of coordinates $\mu - 1/P$,
б - system of coordinates $\mu - 1/P^{h}$.

Taking this idea as a point of departure, let us attempt to connect F_o with the specific unit load P and with the hardness of rubber.

We shall characterize the hardness of rubber by means of a conditional quantity h, confined within the limits 0 - 1. Then F_o can be described in terms of formula

$$F_o = ASP^{1-h} , \qquad (2)$$

inasmuch as the surface area of true contact is proportional to the area of nominal surface of friction S. This formula reflects qualitatively, both the noted facts (the symbatic role of the load and the antibatic role of hardness) and is valid for extreme values of h;

if the body is plastic (h = 0), then the area of contact is proportional to load (F_0 = AN), which brings the

Table 1. The Values of Constants in Formula (3) for Friction of Rubber Against Various Linings.*

Caoutchouc	Fillers	Weight Particles	h	Plexiglass μ_∞	Plexiglass A	AMG-7 μ_∞	AMG-7 A	Steel-25 μ_∞	Steel-25 A
NK	None	0	0.30	0.57	350	0.50	330	0.43	230
	Gas soot	40	0.60	0.57	35	0.50	35	0.43	20
SKB-35	None	0	0.30	0.46	370	0.36	200	0.28	300
	Gas soot	60	0.62	0.47	130	0.38	90	0.30	80
SKN-26	None	0	0.45	0.57	415	0.45	450	0.52	400
	Gas soot	45	0.68	0.62	130	0.35	120	0.59	115
	" "	60	0.75	0.62	75	0.35	70	0.62	75
	" "	120	0.92	0.52	40	0.32	35	0.39	30
	Chalk	60	0.60	-	-	0.35	205	0.57	250
	"	120	0.62	-	-	0.30	60	0.35	35
SKS-30	None	0	0.46	0.70	350	0.60	400	0.60	375
	Graphite	10	0.54	0.53	160	0.54	140	0.62	140
	"	50	0.65	0.55	65	0.54	65	0.51	65
	"	120	0.79	0.38	30	0.50	30	0.38	30
	White soot	50	0.65	0.61	110	0.64	110	0.58	100
	" "	120	0.89	0.49	30	0.51	30	0.48	30
Unspecified	None	0	0.49	0.27	155	0.32	60	0.26	110
	Lamp soot	50	0.70	0.27	90	0.32	20	0.24	35

formula (1) to the law of Amonton (μ = const, see (4)); if the body is absolutely hard (solid) (h = 1), then the area of contact is not affected by load (F_0 = A = const). Substituting (2) in (1) we obtain:

$$\mu = \mu_\infty + \frac{A}{N^h} \quad (3)$$

* Quantity A is given on condition that N is measured in grams.

To test the applicability of this formula*, we must trace experimental data in coordinates $\mu - 1/N^h$, expecting that they will fall onto the straight line of which A is tangent of the angle.

To execute this task, we shall express the hardness of rubber by h within the limits of $0 < h < 1$. Let us make use of the fact that the hardness of rubber, according to GOST'u #263-41 (6), is expressed in units of an instrument (Shor's measurer of hardness), which has limits of 0 to 100, all rubbers fitting into the interval between 20 and 99. Let us regard h as hardness per Shor, divided by 100. Thismethod has an empirical character. Having resorted to it in view of insufficient present-day knowledge of hardness of materials and of mechanical properties of rubber and of friction, let us see to what extent this method is permissible in a realm where the mentioned phenomena are interwoven. Fig. 1b shows that the formula (3) is satisfactory.

Analogous findings (data) were obtained in friction against steel, against aluminum-magnium alloy AMG and against plexiglass of various rubbers based on other caoutchoucs filled with graphite, chalk, soot, and silicon dioxide. The constants of the equation (3) are presented in Table 1. These findings are in agreement with the works (1-3). The fact that μ_∞ is distinguishable from zero speaks against the validity of the theory and formula of Shalamakh (7) $\mu = BN^{-1/3}$, whose experimental data, disagreeing with his own formula, satisfies formula (1).

Table 1 shows that quantity A, which characterizes the forces of adhesion of rubber to lining, is determined

* The noted effect of hardness of rubber and of the specific unit load P could be expressed by formula $F_0/N = f(x)$, where non-dimensional quantity $x = E/P$ is connected not with hardness but with a physically more definite quantity - modulus E. However, attempts at concretization of this formula in the form $f(x) = xe^{-x}$ and others, have at the present time failed to lead to results verifiable by experiment.

in the main - by rubber (and not by the lining), since rubber is the softer material, which adopts itself almost identically to the surface shape of various linings with a hardness much greater than that of rubber; there merely exists a tendency towards increase of A when a shift from coarser linings to soft ones is made in the following sequence: steel - alloy AMG - plexiglass. A similar phenomenon is manifested with considerably greater sharpness when the hardness of rubber is altered (2): its decrease substantially increases A (almost independently from the ways and means of alteration of the hardness of rubber), owing to the increase in surface of true contact.

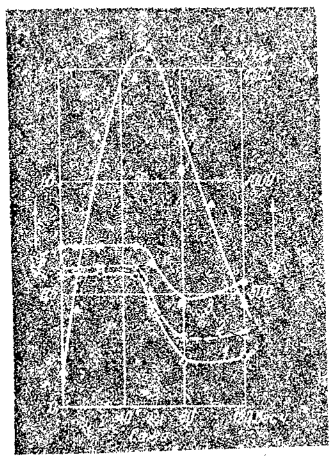

Figure 2. Comparison of the effect of quantity of soot (in rubber of base SKS-30) on the minimal coefficient of friction μ_∞ (curves 1, 2 and 3) and true durability of rubber σ (curve 4).
1 - friction of rubber against steel;
2 - against alloy AMG containing aluminum;
3 - against plexiglass.

Data presented in the table shows that μ_∞ is not altered by the filling in rubber if the filler remains within the limits of compatibility with caoutchouc, i.e., as long as all the particles of the filler are coated with a film of vulcanized caoutchouc. Beyond these limits, when the particles of the filler become a layer between caoutchouc and lining, μ_∞ diminishes.

Such a deduction is confirmed by data in Fig. 2 in which the tear-resistant durability of rubber begins to diminish in the presence of the same quantities of filler which bring about a decrease in μ_∞ because caoutchouc in mixture acquires an intermittent structure. The limit of compatibility corresponds to identical volumes of the quantities of different fillers.

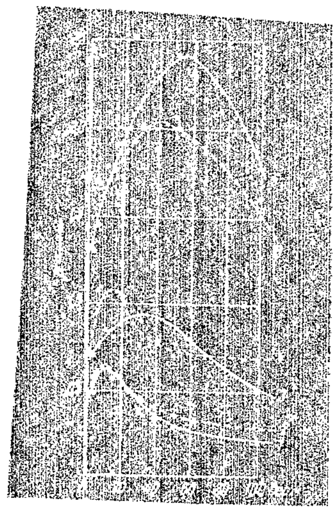

Figure 3. Effect of quantity of softener in rubber (base SKN-26) on the friction coefficient μ at various specific unit loads P: 1 and 2 - P = 10 kg/cm^2; 3 and 4 - 1.3 kg/cm^2, 5 and 6 - 0.1 kg/cm^2, 1, 3 and 5 - softener dibutylcebacinate; 2, 4 and 6 - triethylene-dibuterate.

The effect of a softener on friction of rubber can be regarded as analogous to the influence of a filler. From Fig. 3 one can see that until the softener remains within the limits of compatibility with caoutchouc (i.e., absorbs and swells without sweating), its introduction, while lessening hardness, increases the coefficient of friction, which has its effect on A (and not on μ_∞), i.e., in the realm of small loads (see formula (3)). When, on the other hand, the softener begins to sweat itself out, it plays the role of a lubri-

cant effecting a diminiution of μ_∞ as well, i.e., in the realm of large loads. It is possible that the process of sweating out (pressing out) of the softener is facilitated under large normal loads, which displaces the limit of compatibility.

When quantities of softener go beyond the boundaries of compatibility, friction can no longer be regarded as dry because μ depends (symbatically) on the duration of immobile contact, and the data does not fit into the formula (3) which is valid for friction without lubrication.

Thus, general conclusions: so long as the ingredients of rubber mixture remain within the limits of compatibility with caoutchouc, the quantity μ_∞ (which plays a role at great loads) is independent from the ingredients -- it is determined merely by the interaction of the film of caoutchouc with the lining; the hardness of rubber, which depends on the amount and character of ingredients (fillers, softeners), affects quantity F_0 (including the constant A), which makes a difference at small loads.

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